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Discovery of an extended, halo-like stellar population around the Large Magellanic Cloud

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Abstract. We describe an ongoing, large-scale, photometric and spectroscopic survey of the Large Magellanic Cloud (LMC) periphery. This survey uses Washington $M, T_2 + DDO51$ photometry to identify distant LMC red giant branch (RGB) star candidates; multi-object spectroscopy is used to confirm the stellar surface gravities of these RGB stars and their association with the LMC (e.g., through radial velocities). The survey now encompasses hundreds of fields ranging from the LMC center with full azimuthal coverage around the LMC and out to 23° from the LMC center. We have confirmed the existence of RGB stars with (the unusual) Magellanic velocities out to the radial limit of this survey coverage. From data in a subsample of these fields, we show that this extended population of stars makes up a diffuse structure enveloping the LMC with a two-dimensional distribution resembling a classical halo with a shallow de Vaucouleurs profile and a broad metallicity spread around a typical mean value of [Fe/H] ~ -1.0.

Keywords. surveys, galaxies: evolution, galaxies: halos, galaxies: individual (LMC), Magellanic Clouds, galaxies: structure

1. Introduction and motivation

Recent photometric and spectroscopic surveys have identified extended, metal-poor, Milky Way-like stellar halos around two other Local Group galaxies: M 31 (Ostheimer 2002; Guthathakurta *et al.* 2005; Chapman *et al.* 2006) and M 33 (McConnachie *et al.* 2006; Sarajedini *et al.* 2006). That M 33 is a "dwarf spiral" begs the question of how late in morphological type and low in mass can galaxies have stellar halos. Might Magellanic-sized galaxies also have stellar halos? Certainly cold dark matter (CDM) simulations predict that hierarchical structure formation occurs on *all scales* (e.g., Diemand *et al.* 2007). If the Magellanic Clouds, which probably formed outside the Milky Way (MW) and are only now making their first pass near the Sun (Kallivayalil *et al.* 2006; Besla *et al.* 2007; D'Onghia 2008; see also contributions by these authors in this proceedings), were found to have their own stellar halos, this would provide an opportunity to explore in exquisite detail (nearly as easily as for the MW) two more "independent" galaxy halos and evaluate their structure in the context of prevailing (i.e. CDM) galaxy formation models. We report here the discovery of a large, diffuse structure around the Large Magellanic Cloud (LMC) that is likely that system's stellar halo.

The dominant stellar population of the LMC is its obvious, elongated, exponential stellar disk that extends to $R \sim 9°$ with a radial scale length of $\sim 1.6°$ (van der Marel 2001; Harris 2007) and which has a typical metallicity spanning $-1 \lesssim$ [Fe/H] $\lesssim -0.4$ (Harris & Zaritsky 2004). And, while a population of old, metal-poor RR Lyrae stars with a large velocity dispersion ($\sigma_{\rm v} = 53$ km s^{-1}) has also been found in the LMC, this population apparently follows the exponential density profile of the LMC disk (Minniti *et al.* 2003; Borissova *et al.* 2004, 2006; Alves 2004).

The first hints that there may be a diffuse, dynamically warm and *extended* population around the Magellanic Clouds (MCs) came with the discovery of K giant stars having the approximate distance and mean velocity of the LMC (and SMC) in a probe of several dozen pencil-beam fields encircling the Clouds at distances of $20 - 25°$ from a point midway between the Clouds, as described in Majewski *et al.* (1999) and Majewski (2004). More recently, a significant number of such stars were seen as a colder ($\sigma_{\rm v} = 9.8$ km s^{-1}) moving group serendipitously found in the foreground of fields centered on the Carina dwarf spheroidal galaxy at a remarkably large $R \sim 22°$ from the LMC center (Muñoz *et al.* 2006). The properties of this group of stars — including a mean heliocentric velocity of 332 km s^{-1} and a color-magnitude distribution exactly matching the red clump of the LMC — as well as our ability to track the existence of similar K giants all of the way from Carina back to the LMC (Muñoz *et al.* 2006) prove the existence of MC stars out to these extreme angular separations. However, because of the limited azimuthal distribution of these discoveries about the LMC, it has not been possible to ascertain definitively whether these stars are a bound LMC halo, tidal debris from the LMC (e.g., Weinberg 2000) or SMC (e.g., Kunkel *et al.* 1997), or some other MC-associated population.

2. Systematic survey of the Magellanic periphery

The discovery of these widely separated stars apparently associated with the MCs and the uncertainty of their nature motivated us to undertake a larger and more systematic photometric and spectroscopic survey of the LMC periphery. (This larger survey is part of D. Nidever's Ph.D. thesis.) As in our previous probes around the LMC and in the direction of Carina, we used the *CTIO*-4 m+MOSAIC and *Swope*-1 m CCD cameras to obtain photometry of numerous outlying fields around the LMC in the Washington M and T_2 filters as well as the $DDO51$ filter — a combination of photometric bands that can be used photometrically to discriminate distant giant stars from nearby dwarf stars of similar apparent brightness and color (Majewski *et al.* 2000); the new photometric coverage extends to $R \sim 23°$ and has full azimuthal coverage around the LMC (Fig. 1). Stars are selected to be LMC giant star candidates not only by having color-magnitude combinations appropriate to the LMC red giant branch and red clump, but also ($M - T_2$, $M - DDO51$) combinations appropriate for giant stars (see Majewski *et al.* 2000).

Candidate LMC giant stars identified in this way are then followed up with spectroscopic observations to derive radial velocities and metallicities using a variety of southern instruments. In this contribution, we discuss primarily our first spectroscopic observations from the *CTIO*-4 m+HYDRA multi-object spectrometer in 27 fields (Fig.1).

3. The LMC density and metallicity profiles

Using our photometric and spectroscopic dataset for the 27 fields having Hydra data shown in Fig. 1, plus the MC giants found in the Carina survey of Muñoz *et al.* (2006), we have derived a density profile of the LMC over a radial range of 7–23° from the LMC center (Fig. 2a); these particular fields represent an azimuthal coverage of nearly 180°. Stars used for this radial profile not only pass the photometric criteria for LMC giant stars mentioned above, but also are limited to stars with radial velocities appropriate to the LMC (following a modified van der Marel (2002) LMC velocity model). Because the spectroscopic data used to check velocity membership do not completely sample the photometrically-selected LMC giant star candidates (e.g., because of limits to the Hydra

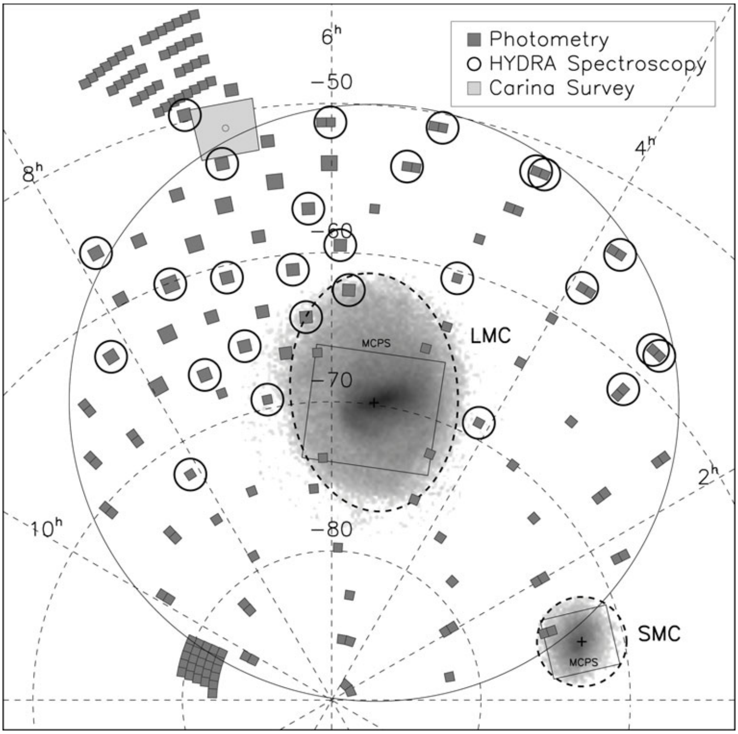

Figure 1. Map of our new survey of the LMC periphery in celestial coordinates. The background greyscale image shows the density of LMC and SMC red giant branch stars selected from 2MASS. Photometrically targeted fields from the *Blanco* telescope+MOSAIC and from the *Swope*-1 m imager are represented by dark shaded boxes lying mostly beyond the obvious 2MASS distribution. The circled boxes indicate fields with *Blanco*+HYDRA multi-object spectroscopy (27 fields). The large, lightly shaded box indicates the area covered by the Carina survey of Muñoz *et al.* (2006), where the 332 km s^{-1} group was found. The large circle has a radius of 20° from the LMC center. The extent of the Magellanic Clouds Photometric Survey (MCPS; Zaritsky *et al.* 2002, 2004) is indicated by the large boxes inside the LMC and SMC.

field size and constraints on fiber placement), we correct the giant star densities in each field for both the sampling and success fractions in each field; consequently, the derived densities shown in Fig. 2a are mostly, but not completely spectroscopically derived.

The observed density profile in Fig. 2a is inconsistent with a single density law over the radial range explored. More specifically, the inner density profile is matched by the known exponential LMC disk profile (e.g., radial scale length of 1.6°; van der Marel 2001) out to $R \sim 9°$ (the large scatter at small radii is due to the elongation and inclination of the LMC disk). However, beyond this radius, the profile flattens and begins to resemble the halos seen in other galaxies. This new, extended component of the LMC is well-fitted by either a de Vaucouleurs profile with a core radius of 2.4° or an exponential with a radial scale length of 4.1°. In the fields beyond $R = 9°$, the spectroscopically-derived radial profile (i.e. Fig. 2a) shows no obvious global asymmetry with position angle — consistent with a nominal halo but generally not for tidal debris; however, this profile is derived from the limited azimuthal coverage of the Hydra-investigated fields (see Fig. 1).

To test this azimuthal symmetry further, in Fig. 2b we plot densities for all photometrically-selected LMC giant star candidates in fields with *CTIO*-4 m+MOSAIC photometry to $R \sim 13°$ regardless of spectroscopic coverage (the densities beyond $R \sim 13°$ are so low that spectroscopic data are required to calculate them reliably). A nominal background

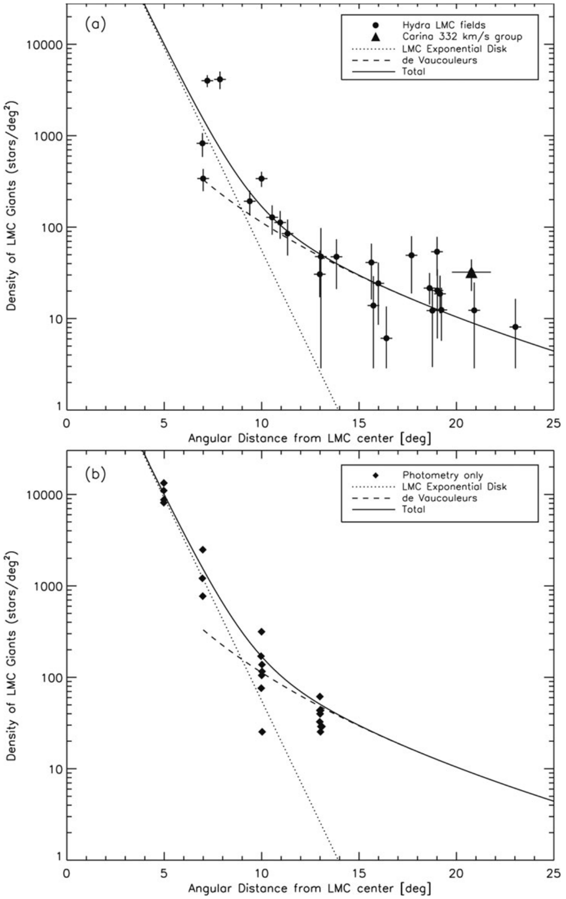

Figure 2. (a): Spectroscopically-determined density profile of LMC giants from the Hydra fields in Fig. 1. Densities in each field are incompleteness-corrected by applying RV-membership fractions in the spectroscopic sample to remaining photometric candidates without spectroscopy. Inner fields match the nominal LMC exponential disk profile with 1.6° scale length previously detected to $R \sim 9^\circ$ (dotted line). The newly found, extended LMC population beyond $R = 9^\circ$ can be fitted by a de Vaucouleurs profile with 2.4° core radius or an exponential of scale length 4.1° (dashed line). The initial discovery of this population in the foreground of the Carina dSph is indicated by a triangle. **(b):** LMC density profile from photometrically-selected, "LMC-like" giant stars for all survey fields with *CTIO*-4 m+MOSAIC data to $R \sim 13^\circ$ with an appropriate background subtraction (see text). The $R \sim 13^\circ$ densities clump very tightly around the de Vaucouleurs profile for all azimuthal angles (showing the radial symmetry of the density law) and well above extrapolation of the LMC disk exponential. The lines are the same as in (a).

density, calculated by using the LMC giant star selection in the $(M - T_2, M - DDO51)$ diagram but applied to other magnitudes in the color-magnitude diagram (a method we have successfully used in other studies), has been subtracted for each field. The photometrically-derived density profile (Fig. 2b) has nearly full azimuthal coverage and shows not only that the LMC giant candidate densities at $R \sim 13^\circ$ are well above the density level predicted by extrapolation of the exponential disk, but fall along the combined two-component profile derived in Fig. 2a with very little scatter. The narrow dispersion of densities in Fig. 2b and lack of any position angle-dependencies in the spectroscopic density profile in Fig. 2a indicate that the newly found extended component of the LMC is azimuthally symmetric — as expected for a classical stellar halo.

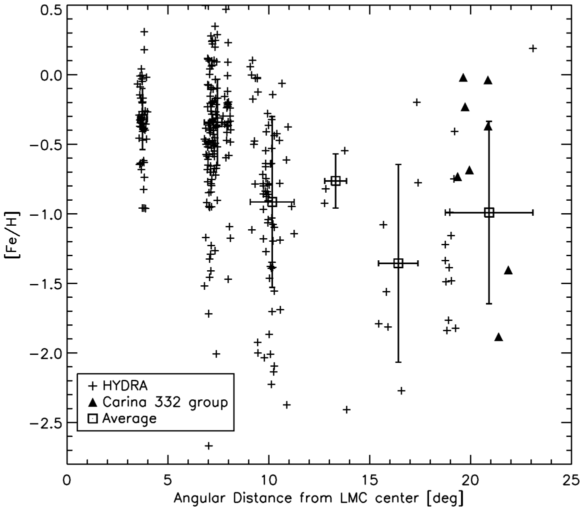

Figure 3. Spectroscopic metallicity profile of our LMC stars. Triangles represent the 332 km s^{-1} moving group found in the Carina survey. Open squares show averages in radial bins, while bars around these squares represent the dispersions in quantities in each bin.

Our spectra cover the wavelength range 4500−7300 Å. We have calculated spectroscopic metallicities for our stars using Lick indices. Metallicity results presented here come from measurement of six iron lines in the above wavelength region calibrated against a large grid of spectroscopic standard stars (Schiavon 2007). The metallicity profile ([Fe/H] vs. radius) shown in Fig. 3 derives from those stars with the most reliable [Fe/H] measurements (with typical errors estimated to be ~ 0.4 dex), and confirms that there is a transition from dominance of the LMC disk population at [Fe/H] ~ -0.4 to a different population of lower metallicity at large radius. Stars from this more metal-poor, outer population start to appear in fields at $R \sim 7°$. Thus there is an overall radial gradient seen in the LMC profile, but at all radii there is a large spread in metallicity.

4. Origin of the new population

What is the origin of this new LMC population? An LMC halo could be created by an “outside-in” process similar to the one hypothesized for formation of the MW halo by the accretion and merger of smaller systems. Cosmologically-driven N-body simulations of structure formation (e.g., by Diemand *et al.* 2007) indicate that the satellites of MW-like galaxies (e.g., the LMC) should have their own substructure.

Clues to the origin of the outer population may lie in the metallicity profile in Fig. 3. While the sample of spectroscopic metallicities at large radii is still small, it suggests a mean metallicity for the outer LMC population of [Fe/H] ~ -1, but with stars spanning an enormous range, from [Fe/H] < -2 to about solar. This mean metallicity is higher than the metal-poor halos of either the MW or M 31 (Kalirai *et al.* 2006); if stellar halos form from the accretion of smaller systems, and such systems generally follow a mass–metallicity relationship, one might expect the mass spectrum of accreted subhalos for the LMC to promote the creation of a halo of overall lower metallicity. On the other hand, the impression from Fig. 3 is that the metallicities of outer LMC stars are not well-mixed. While admittedly it might be premature to conclude that this is a result of other than statistical fluctuations, an inhomogeneous metallicity distribution is what one expects from hierarchical halo formation, and were the LMC halo dominated by the contribution of a few of its largest subhalos, this could skew the metallicity distribution and mean metallicity over the small number of large radius fields we have sampled.

Alternatively, the newly found outer LMC population might have originated via an “inside-out” scenario — e.g., one in which the LMC disk is kinematically “puffed up” by dynamical interactions with the MW and stars at the edge of the disk are liberated into the LMC surroundings (Weinberg 2000). However, this scenario would require the LMC disk to contain rather metal-poor stars to account for those seen at large radii. Moreover, if the Magellanic Clouds are on their first passage by the MW (see references in §1), the inside-out scenario, which depends on multiple orbits of the LMC around the MW, is much less likely. Finally, the Weinberg (2000) models show a density distribution for the liberated disk stars with significant azimuthal asymmetry.

In future work we will analyze a much larger spectroscopic sample than that discussed here and derive the detailed velocity field and chemical abundance distributions of stars in this newly found MC population. Such data will help clarify the origin of these newly identified, widely separated Magellanic stars.

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